A Control Strategy for Implementation of Enhanced Voltage Quality in Micro Grid

G. Tabita, B. Satish

***Abstract*— This paper presents series/shunt control strategy for improving the voltage quality in grid interfacing system.**

The micro grid concept using renewable energy sources is a building block towards the future energy networks for long-term viable solutions of energy needs. The combination of wind energy and solar energy with local energy storage devices may reduce vulnerability to natural disasters because they do not require lifelines.

Experiments with a concrete laboratory system are given to detail the proposed concepts and to demonstrate the practical implementations. Two three-phase four-leg inverters, together with dc micro-sources and nonlinear loads, are employed to construct a general series parallel grid-interfacing system.

The energy obtained from the energy sources may contain harmonics and leads to distortion in output voltage. This distortion can be eliminated by using proper control strategies and filters in both the series and shunt converters. Simulation study is carried out in MATLAB software package

***Index Terms*— Grid, Series Inverter, Shunt Inverter, Micro Grid, Renewable Energy Sources**

I. INTRODUCTION

Increasing electrification of daily life causes growing electricity consumption, rising number of sensitive/critical loads demand for high-quality electricity, the energy efficiency of the grid is desired to be improved, and considerations on climate change are calling for sustainable energy applications [1][2]. All these factors are driving the conventional electricity grid to the next generation of grid, i.e. smart grid, which is expected to appear and coexist with the existing grid, adding to its capacity, reliability, and functionalities [3].

The integration of Renewable energy sources and energy storage systems has been one of the new trends in power electronic technology. The increasing number of Renewable energy sources and distributed generators require new strategies for their operations in order to maintain or improve the power supply quality and stability.

High prices of oil and global warming make the fossil fuels less and less attractive solutions. Wind power is a very important renewable energy source. It is free and not a polluter unlike the traditional fossil energy sources. It obtains clean energy from the kinetic energy of the wind, by means of the wind turbine .The wind turbine transforms the kinetic wind energy into mechanical energy through the drive train and then into electrical energy by means of the generator.

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Solar energy is also one of the important renewable energy source. Photo voltaic (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic power generation employs solar panels comprising a number of cells containing a photovoltaic material . There are different Tracking systems available for the solar panels. To get solar power more efficiently a Maximum Power Point Tracker (MPPT) is used that functions the photovoltaic (PV) modules in a way that allows the PV modules to produce all the power they are capable of. It is not a mechanical tracking system which moves physically the modules to make them point more directly at the sun. Since MPPT is a fully electronic system, it varies the module's operating point so that the modules will be able to deliver maximum available power. As the outputs of PV system are dependent on the temperature, irradiation, and the load characteristic MPPT cannot deliver the output voltage perfectly. For this reason MPPT is required to be implementing in the PV system to maximize the PV array output voltage.

This paper focuses on the grid-interfacing architecture, taking into account how to interconnect DG systems in the future grid with enhanced voltage quality. The desirable approach should be able to maintain high-quality power transfer between DG systems and the utility grid, even in disturbed grids, and be able to improve the voltage quality at both user and grid side. Figure 1 shows an example of the future application of grid-interfacing converters. On the left-hand side, multiple DG systems together with energy storage and local loads are interconnected to construct a microgrid. Energy storage systems (e.g., supercapacitor, battery, fuel cell, etc. [9]) are used to store excess energy from the microgrid and send the stored energy back to the grid when needed, which are necessary for microgrid applications. As a basic structure of the smart grid, plug-and-play integration of microgrids is essential, which can function whether they are connected to or separate from the electricity grid [10]. On the right-hand side, a bidirectional series converter, which is supplied with distributed source and energy storage, interfaces the Microgrid to a utility grid (can be another microgrid) for exchanging power and isolates grid disturbances from each of the grids. The data bus indicates network-scale communication path for variable collection and exchange in smart grid. Starting with the possibilities of future grid-interfacing architecture, this paper adopts the conventional series-parallel structure to construct a grid-interfacing converter system. By reconfiguring the system functionalities, a versatile power electronics-based interface is derived for DG applications, voltage quality enhancement, and flexible power transfer [11]. Experiments with a concrete laboratory system are given to detail the proposed concept and to demonstrate the practical implementation.

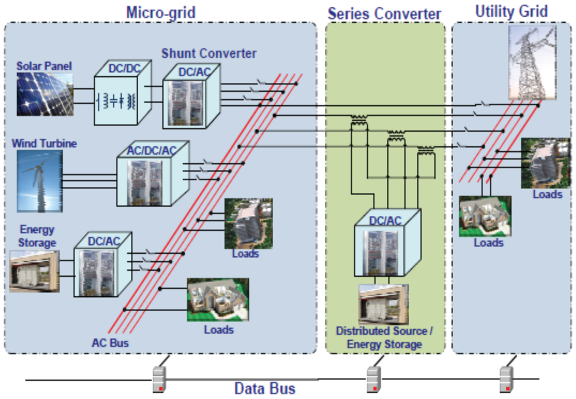


Fig. 1. An example of the future application of grid-interfacing converters for connecting multiple DG systems to the utility grid.

II. Grid Interfacing System

This section presents possible system configurations base on the conventional series-parallel structure and, moreover, retailors the functionality of the adopted system. The features of the proposed system are discussed in terms of system structure, control objectives, and smart grid applications.

Figure 2 shows an example of the future application of grid-interfacing converters. On the lefthand side, multiple Distributed Generation (DG) systems consisting of Solar Energy and Wind Energy together with energy storage and local loads are interconnected to construct a microgrid. The Energy storage systems (e.g., supercapacitor, battery, fuel cell, etc.) are used to store excess energy from the microgrid and send the stored energy back to the grid when needed, which are necessary for microgrid applications.

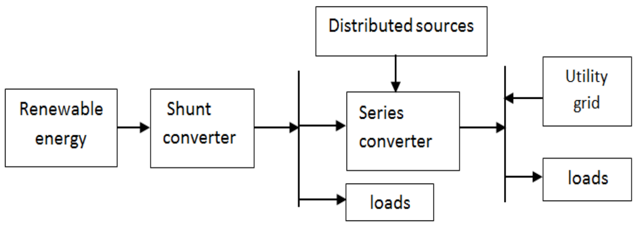


Fig 2: Grid Interfacing Converters

A. *Series Parallel Systems*

Fig 3 & Fig 4 shows the overall control structure of the series parallel system, which consists of reference signal generation and two individual controllers. A basic block, the symmetric sequence voltage detection and synchronization,is essential to determine the fundamental positive- and negative sequence voltage, as well as the grid frequency. This information is important for both converters in order to synchronize with the grid and to design control reference signals.

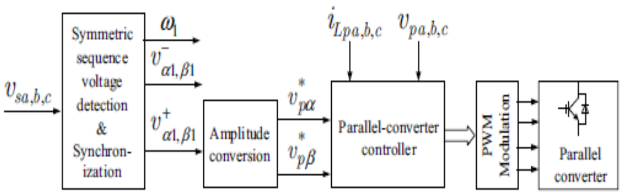


Fig 3: Block diagrams of the overall control structure of parallel Converter

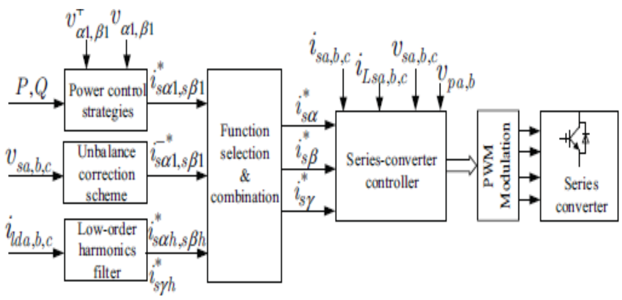


Fig 4: Block diagrams of the overall control structure of series converter.

As shown in Fig. 3 , based on the fundamental positive sequence grid voltages $(v_{\alpha 1}{}^{+}, v_{\beta 1}{}^{+})$ derived in the stationary frame, the amplitude conversion block first shapes the signals to per-unit quantities and then generates a set of reference signals $(v_{p\alpha}{}^{*}, v_{p\beta}{}^{*})$ with a specified amplitude for the parallel converter.

The series converter is applicable for achieving multilevel control objectives. Hence, the block "function selection and combination" in Fig. 4 indicates that different objectives can be integrated into the system by choosing appropriate reference signals $i_{s\alpha}{}^{*}$, $i_{s\beta}{}^{*}$, $i_{s\gamma}{}^{*}$. Details about the unbalance correction scheme, which is used to generate current reference for negative-sequence voltage compensation. For the power control strategy, which are used to obtain desired currents for active/reactive power transfer. Due to the space limitation, they are not duplicated here. The active filter function is represented by the block "loworder harmonics filter". References of low-order current harmonics, denoted by $i^{*}_{s\alpha,s\beta,s\gamma}$, can be obtained. In order to track the desired reference signals, the rest of this section presents the main design aspects of the series and parallel converter control.

B. *Control of Parallel Inverter*

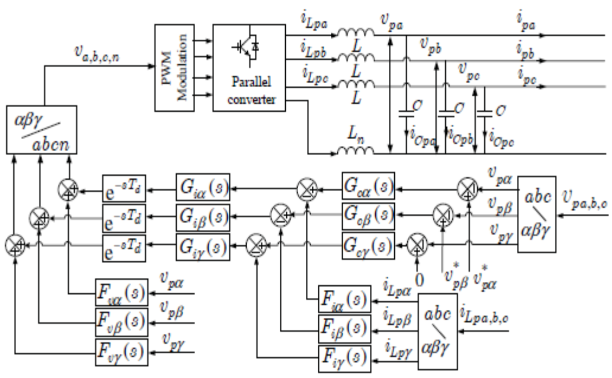


Fig. 5. Control diagram of the parallel converter.

The control diagram of the parallel-converter is shown in Fig. 5, where the sampling and transfer delay of the control is considered and represented by $e{-}sTd$. System parameters are provided in the section of experimental results. Simplifying the inverter to have a unity gain, the average model of the α-quantities in the proposed control scheme is shown in Fig 6 In the stationary frame, the α, β, and γ quantities are decoupled and their control designs are similar.

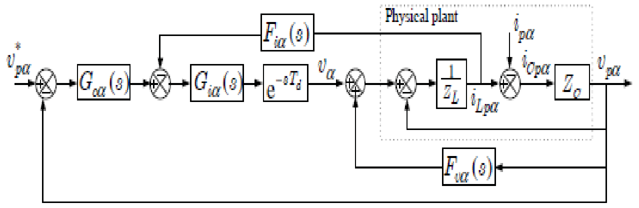


Fig. 6 Block diagram representation of the α-quantities in Fig 5

i. System Instability Improvement

A voltage feed forward loop can usually be used to improve system dynamics. It is shown in this section that this loop can also eliminate the instability of parallel converters under no-load conditions. When the parallel converter is not connected to local loads and also does not deliver power to the grid, the output current *ipα* in Fig.6 equals to zero. The transfer function of the physical plant (from the inverter output *vα* to the filter output *vpα*) in Fig.6 can be expressed as

$$G_{pl}(s) = \frac{v_{p\alpha}}{v_\alpha} = \frac{Z_C}{Z_L + Z_C}, \quad (1)$$

with *ZL* = *sL* + *RL* and *ZC* = *RC* + 1 *sC* , where *RL* and *RC* are the equivalent series resistors (ESR) of *L* and *C*, respectively.

Taking in to account the sampling and transfer delay in the feed forward loop , it follows that

$$F_{v\alpha}(s) = K_{ff}e^{-sT_d} \approx K_{ff}\frac{1 - sT_d/2}{1 + sT_d/2}, \quad (2)$$

Where is the forward gain , is the sampling period ,In order to observe the effect of the feed forward loop on the physical plant , the inductor current loop is excluded by setting , therefore after including the voltage feed forward loop , the transfer function from to is obtained as

$$G_{pl-ff}(s) = \frac{v_{p\alpha}}{v_\alpha} = \frac{G_{pl}(s)}{1 - G_{pl}(s)F_{v\alpha}(s)}. \quad (3)$$

Frequency response of $G_{pl\text{-}ff}(s)$ are plotted with different K_{ff} if $K_{ff}=0$, then $G_{pl\text{-}ff}(s) = G_{pl}(s)$, a sharp increase of the amplitude and a 180 degree phase shift appear at the resonance frequency of the LC filter tank. This limits the control band width and also makes the controller design difficult.

ii. Selective Harmonic Regulation

Before studying the inner current-loop, the external voltage control-loop is first analyzed. Because the adopted grid-interfacing system is a four-wire system and will be explored with asymmetrical nonlinear loads, triplen odd harmonic components will also appear in the line. In order to prevent the output voltage from being distorted under nonlinear load conditions, multiple PR controllers are employed as compensators for voltage regulation at selected harmonic frequencies, expressed as by

$$G_{c\alpha}(s) = K_P + \sum_{n=1,3,5,7}^{9} \frac{2\omega_{bn}K_{In}s}{s^2 + 2\omega_{bn}s + (n\omega_c)^2}, \quad (4)$$

where the resonant terms at 1st, 3rd, 5th, 7th, and 9th harmonics are selected, with KP = 0.55,KI1 = 50,KI3,5,7,9 = 20, ωb1 = 10 rad/s, ωb3,5,7,9 = 6 rad/s, and ωc = 314 rad/s. It can be seen that the open-loop gains at selected frequencies are enhanced so as to fully compensate the voltage harmonics at these frequencies.

iii. Disturbance Sensitivity Improvement

The inner current loop is used to improve system sensitivity to the disturbances on the output current ipα. Since the voltage regulation loop plus the feed forward loop have already pushed the system bandwidth to 1.2 kHz with a phase margin of 20◦, the inner current compensator Giα(s) can hardly increase the bandwidth. In order to maintain the characteristics of the system control at low-order harmonic frequencies, a unity gain is assigned to the inner current regulator, that is Giα(s) = 1, and only high-frequency components of the inductor current are sampled. Thus, current feedback loop is expressed as

$$F_{i\alpha}(s) = K_{fI}\frac{s}{s + 2\pi f_{hp}}, \quad (5)$$

where *KfI* is the current feedback coefficient and *fhp* the high pass bandwidth. the system sensitivity to current disturbances can be obtained, i.e.

$$G_d(s) = \left.\frac{v_{p\alpha}(s)}{i_{p\alpha}}\right|_{v^*_{p\alpha}=0}, \quad (6)$$

C. Control of Series Converter

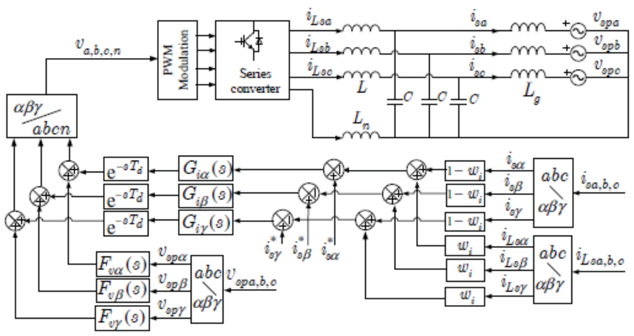


Fig 7: Control diagram of the Series converter

The control consists of a voltage feed forward loop and a current feedback-control loop. As an additional voltage feed forward loop, it is used to decouple the influence of grid voltage disturbances on the output current isα, thereby improving system dynamics. Fvα(s) is simply a unity gain. In the rest of this subsection, only the current feedback-control loop is specified.

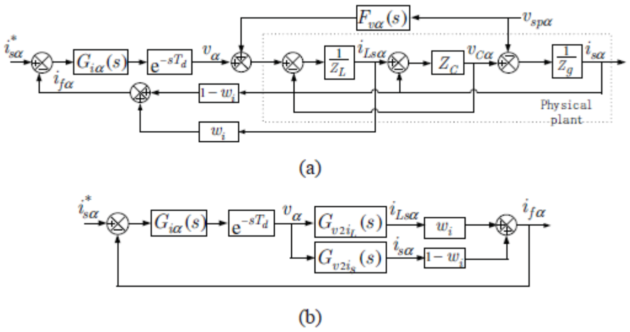


Fig 8: Block diagram representation of (a) the average model of the α-quantities in Fig.7 and (b) the small-signal model.

Disregarding the ESRs of the inductor and the grid impedance, the transfer function from the inverter output voltage to the inductor current and the grid current are expressed, respectively, as

$$G_{v2i_L}(s) = \frac{i_{Ls\alpha}}{v_\alpha} = \frac{L_g C s^2 + 1}{L L_g C s^3 + (L + L_g)s}, \quad (7)$$

and

$$G_{v2i_s}(s) = \frac{i_{s\alpha}}{v_\alpha} = \frac{1}{L L_g C s^3 + (L + L_g)s}. \quad (8)$$

By introducing a weighting factor *wi* for the two currents, from the above figure, the modified system transfer function from the inverter output voltage *vα* to feedback current *ifα* is obtained, i.e.

$$G_{v2i_f}(s) = w_i \frac{L_g c s^2 + 1}{L L_g c s^3 + (L + L_g)s} + (1 - w_i)\frac{1}{L L_g c s^3 + (L + L_g)s} \quad (9)$$

When wi = 0, the control model in Fig.8 represents grid current feedback control, and when wi = 1, it represents inductor current feedback control

$$G_{v2i_f}(s) = \frac{1}{s L_{sum}}. \quad (10)$$

Therefore, the third-order system is turned into a firstorder system, implying that the resonance problem is eliminated. For the purpose of suppressing harmonic currents, the current compensator *Giα*(*s*) is designed with the multiple PR controller . In the experiment, the resonant terms are only selected at the 1st, 3rd, 5th, and 7th harmonic frequencies.

III. SIMULATION RESULTS

The parameters of system are given below

TABLE-I System Papramerers

Description	Symbol	Value
Rated grid voltage	*Vga,b,c*	230V/50Hz
Grid impedance	*Zg*	2 mH (ESR 0.628 Ω)
Output inductor	*L*	1.8 mH (ESR 0.03 Ω)
Output capacitor	*C*	5 μF
Neutral inductor	*Ln*	0.67 mH (ESR 0.02 Ω)
Series transformer	*TN*	1 : 1
dc-link voltage	*Vdc*	750 V
dc-link capacitors	*Cdc*	4400 μF
Switching frequency	*fsw*	16 kHz
Sampling frequency	*Fsp*	8 kHz

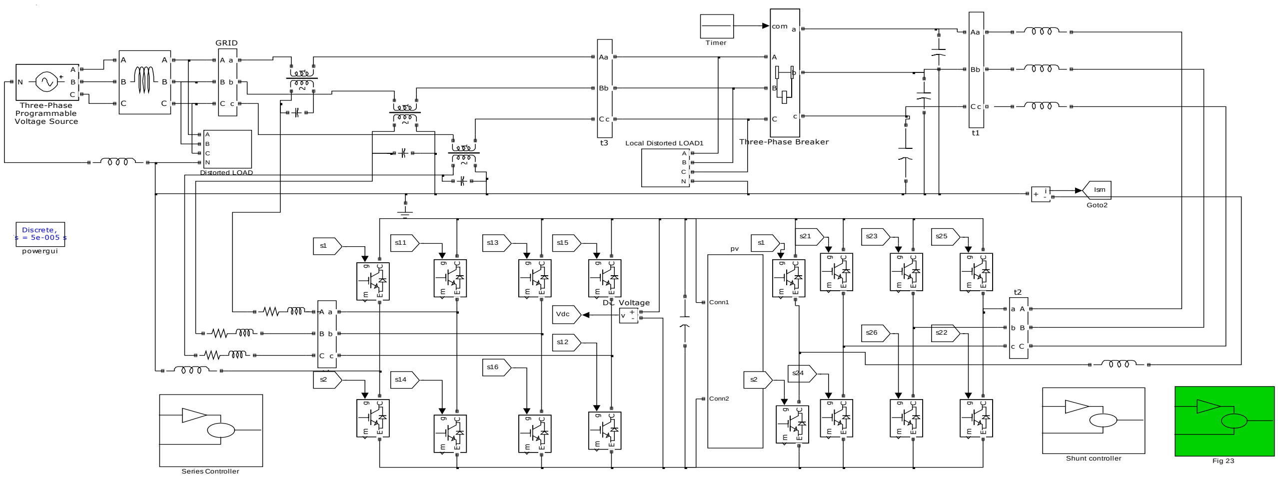
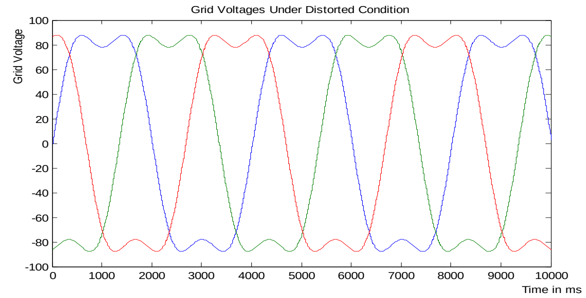
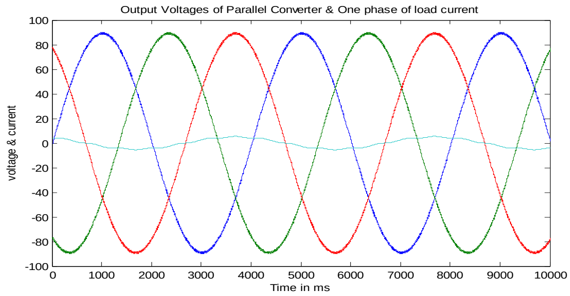


Fig 9: Simulation Implementation of Micro Grid



(a)



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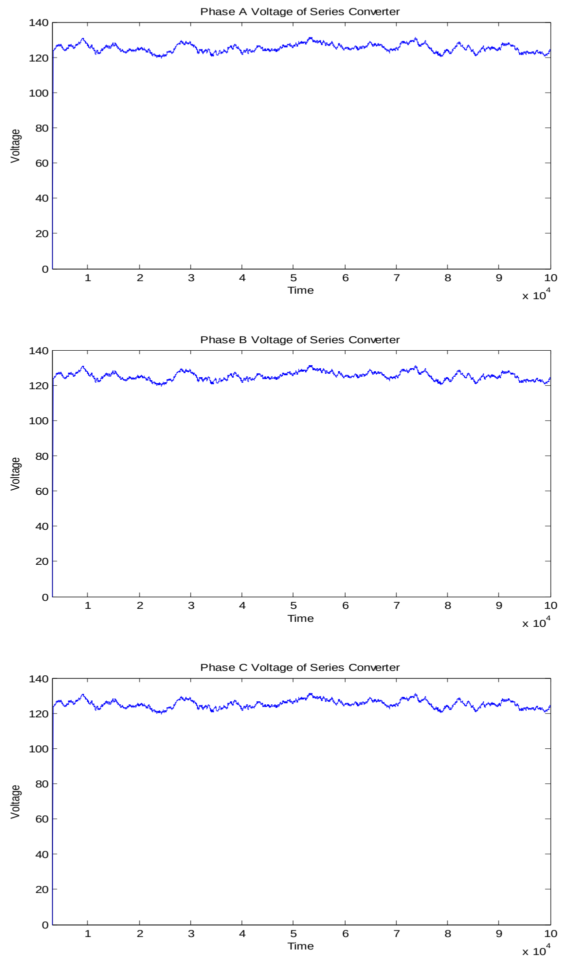
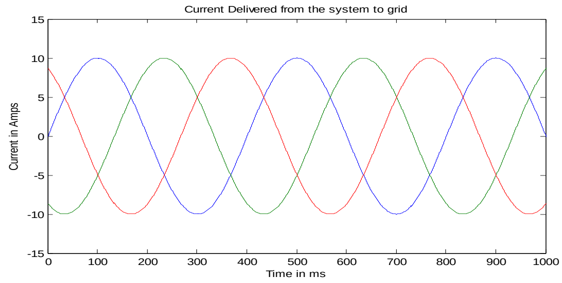
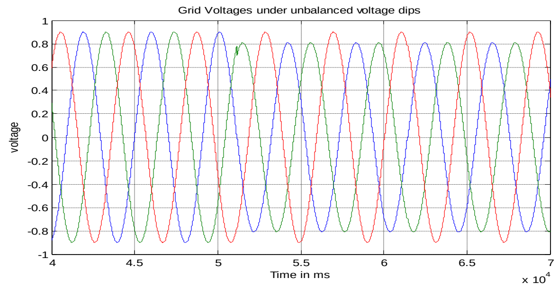


(c)

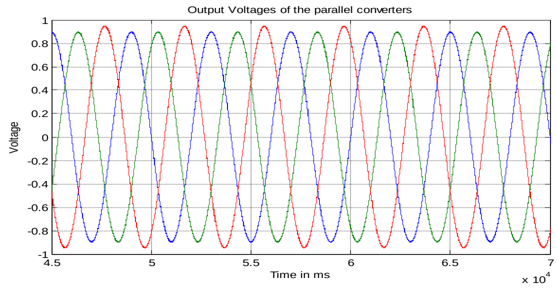


(d)

Fig 10: Experimental results of the series-parallel system under a distorted grid: (a) grid voltages, (b) output voltages of the parallel converter and one phase of the load currents, (c) output voltages of the series converter, and (d) currents delivered from the system to the grid.



(a)



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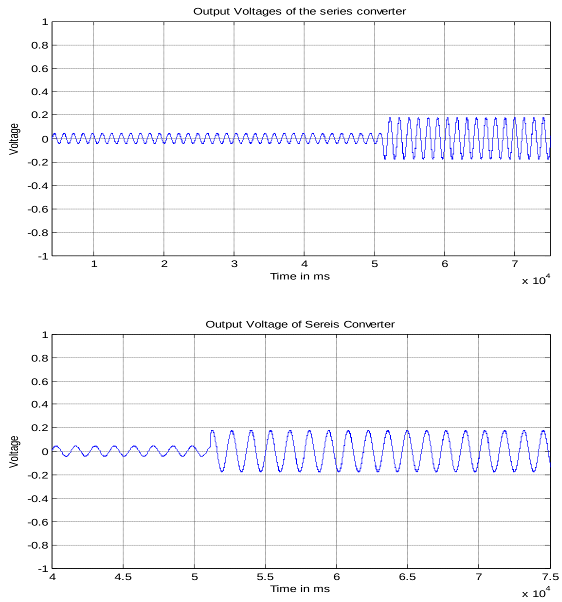
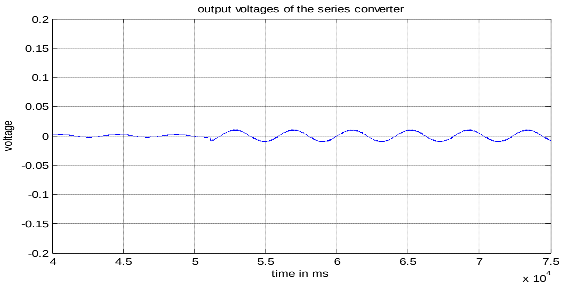
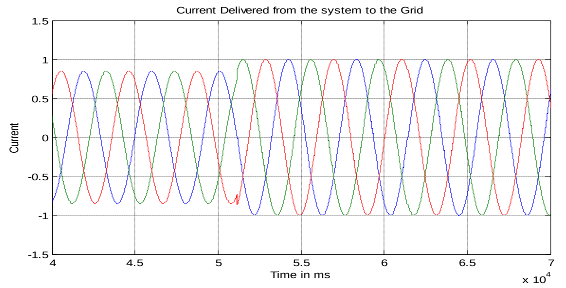




(c)



(d)

Fig. 11. Experimental results of the series-parallel system under unbalanced voltage dips: (a) grid voltages, (b) output voltages of the parallel converter, (c) output voltages of the series converter, and (d) currents delivered from the system to the grid.

A. System Test Under Distorted Grid Conditions

The entire system was tested with a distorted grid having a voltage THD around 6.7%. As shown in Fig. 10 (a), the distorted voltage involves 5% of 3rd harmonic, 4% of 5th harmonic, and 2% of 7th harmonic. The output voltages of the parallel converter together with one phase current of the local loads are given in Fig. 10 (b), showing good voltage quality. The series converter therefore injects quite distorted voltages, as shown in Fig. 10 (c), in order to deliver balanced and sinusoidal grid currents. The resulting grid currents are shown in Fig. 10 (d), with a THD about 3.5%.

B. System Test Under Unbalanced Voltage Dips

The entire system was tested with unbalanced voltage dips. As shown in Fig. 11 (a), starting from a balanced grid condition, the voltages of phase *a* and *b* dip to 80%. In Fig. 11 (b), it is shown that the output voltages of the parallel converter are very stable and are kept balanced and sinusoidal. The series converter therefore immediately injects unbalanced voltages after voltage dips, as shown in Fig. 11 (c), so as to protect the local system from the grid disturbances and to maintain constant active power delivery to the grid (Fig. 11 (d)). The grid currents (THD = 4.6%) after the transient of voltage dips still comply with harmonic requirements.

CONCLUSION

This paper has introduced system-level concept and implementation aspects aiming at grid-interfacing architecture in the future grid with enhanced voltage quality. A group of series-parallel grid-interfacing system topologies have been proposed. They are suitable for DG applications, voltage quality improvement, and power transfer. With the reconfigurable functionalities, the proposed systems have been compared with conventional series-parallel systems and shunt-connected systems, showing flexible applicability.

To specify the proposed concepts and system control, a laboratory set-up has been designed. By defining multi-level control objectives for the system module, it has been shown that the proposed system can ride through grid disturbances, maintain good-quality voltage and achieve flexible power control. Also, the possibilities to integrate auxiliary functions like grid unbalance correction and harmonic current compensation into the system have been detailed.

Finally, the entire control design of the series and parallel converters have been presented, where the main design aspects of the controllers have been highlighted. The proposed methods have been verified by experimental tests on the laboratory setup.

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